

LETTER TO THE EDITOR

# XMM-Newton RGS spectrum of RX J0720.4–3125: An absorption feature at 0.57 keV<sup>★</sup>

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## ABSTRACT

**Aims.** By measuring the gravitational redshift of spectral features in the spectrum of thermal radiation emitted from neutron stars, useful constraints for the equation of state of superdense matter can be obtained via an estimate of the mass-to-radius ratio. We searched for spectral line features in the high-resolution X-ray spectrum of the isolated neutron star RX J0720.4–3125.

**Methods.** Our target was observed by *XMM-Newton* on many occasions. We used the *XMM-Newton* SAS task *rgscombine* in order to create a co-added RGS spectrum of RX J0720.4–3125. We modeled the resulting spectrum with absorbed blackbody radiation with a Gaussian absorption features using the XSPEC package.

**Results.** We found a narrow absorption feature at 0.57 keV in the co-added RGS spectrum of the isolated neutron star RX J0720.4–3125 with an equivalent width of  $1.35 \pm 0.3$  eV and FWHM  $\sim 6.0$  eV. The feature was identified with an absorption line of highly ionized oxygen O VII, most probably originating in the ambient medium of RX J0720.4–3125. An extensive investigation with the photo-ionization code CLOUDY indicates the possibility that the optical flux excess observed in the spectrum of RX J0720.4–3125 at least partially originates in a relatively dense (e.g.  $n_H \sim 10^8 \text{cm}^{-3}$ ) slab, located in the vicinity of the neutron star (e.g.  $\sim 10^{10} \text{cm}$ ).

**Key words.** RX J0720.4–3125–Isolated neutron stars – X – ray spectrum – ISM

## 1. Introduction

The study of thermally emitting and radio-quiet, nearby, isolated neutron stars (INSs) may allow an important input to our understanding of neutron stars. In particular, measuring the gravitational redshift of a spectral feature in the spectrum of thermal radiation emitted from the neutron star surface (atmosphere) may provide a useful constraint for various equations of state for superdense matter. Independent of the estimate of the neutron star radius (e.g. Trümper et al. 2004) from the thermal spectrum of an INS, it will also allow us to directly estimate the mass-to-radius ratio. RX J0720.4–3125, originally discovered as a soft X-ray source during the *ROSAT* All-Sky Survey by Haberl et al. (1997), is a special case among the INS. Clear spectral variations on times scales of years were detected during *XMM-Newton* observations in the data of the high spectral resolution Reflection Grating Spectrometers (RGS) (de Vries et al. 2004) and the imaging-spectroscopic instrument EPIC pn (Haberl et al. 2006). However, during individual RGS observations the number of counts received from RX J0720.4–3125 in a single resolution element were not enough to study the spectrum in detail.

From this point of view, it is interesting to study a co-added *XMM-Newton* RGS spectrum of RX J0720.4–3125, despite of the spectral variations shown by the INS.

**Table 1.** *XMM-Newton* RGS1/2 observations of RX J0720.4–3125

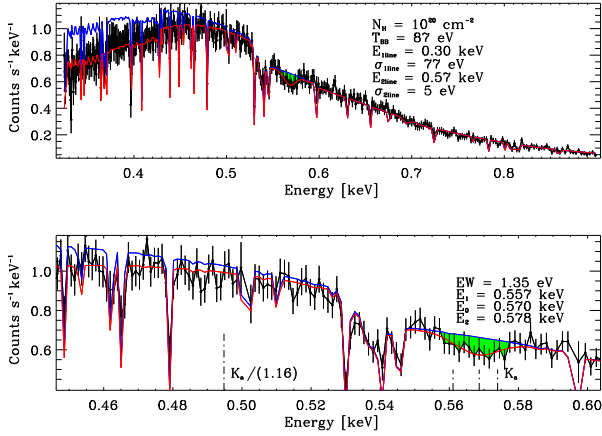
Obs. ID	Obs. Date Start JD - 2400000	Exposure ksec	Effective exposure ksec
0124100101	51678.1503935	65.87	15.45
0132520301	51870.2714931	30.91	30.24
0156960201	52585.2443171	30.24	29.60
0156960401	52587.3090509	32.04	31.03
0158360201	52762.0499190	81.63	73.43
0161960201	52940.2405093	44.92	44.67
0164560501	53147.9273380	51.95	44.36
0300520201	53488.8618634	53.31	50.69
0300520301	53636.4891551	53.01	51.38
0311590101	53687.4349306	39.71	38.91
0400140301	53877.6977662	21.91	21.57
0400140401	54044.9718634	21.91	21.69
0502710201	54226.2093171	21.91	21.57
0502710301	54421.7184259	24.92	24.59

## 2. Observations and data reduction

RX J0720.4–3125 has been observed many times by *XMM-Newton* (Hohle et al. 2009) and we focus here on the data collected with RGS (den Herder et al. 2001) from the 14 publicly available observations, in total presenting about 500 ks of effective exposure time.

The data were reduced using standard threads from the *XMM-Newton* data analysis package SAS version 8.0.1. We reprocessed all publicly available data (see Table 1) with the stan-

<sup>★</sup> Based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA



**Fig. 1.** *XMM-Newton* high-resolution co-added spectrum of the isolated neutron star RX J0720.4–3125. An absorbed blackbody (blue) and an absorbed blackbody with two additional Gaussian absorption lines (red, a wide absorption feature at 0.3 keV and a narrow feature at 0.57 keV) are shown. The equivalent width and the FWHM of the narrow absorption line (green), which we associate with OVII, were determined at 1.35 eV and  $\sim 6.0$  eV, respectively. Different spectral line positions at gravitational redshift ( $g_r = 0$ ) are indicated.

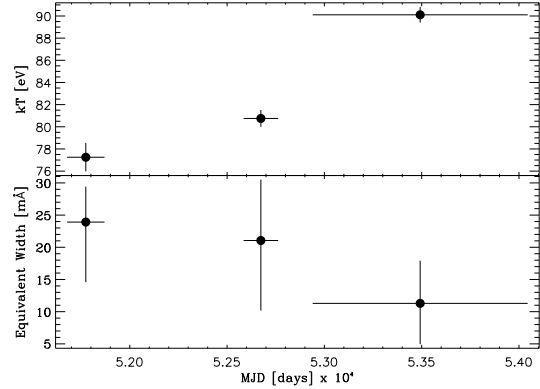
ard metatask *rgsproc* with the aim to co-add the spectra with the task *rgscombine*. To determine good time intervals free of background flares, we used the filtering expression ‘rate < 1.0’ on the background light curves. This reduced the total exposure time by  $\sim 13\%$ . First order source and background spectra were produced from the cleaned events. A model background spectrum was also generated with the task *rgsbkgmodel* that also was used for the background correction as an additional check for possible phenomena related to background variations seen during some of the observations. No significant differences between RGS spectra reduced in these two different ways were seen.

The background subtracted co-added spectra of RX J0720.4–3125 revealed the existence of a relatively narrow absorption-like feature at  $\sim 0.57$  keV. No sharp variation is present in the spectral response of the instrument, indicating an astronomical origin. A similar narrow absorption feature was reported in the *XMM-Newton* RGS spectrum of another INS RX J1605.3+3249 at 0.576 keV by van Kerkwijk et al. (2004).

We fitted the resulting co-added RGS1<sup>1</sup> spectrum of RX J0720.4–3125 (see Fig. 1) using the *XSPEC* package version 12.5.0. We fitted an absorbed blackbody model with a broad (0.08 keV) Gaussian absorption feature at 0.3 keV, well known from *XMM-Newton* EPIC pn spectral studies (Haberl 2007).

Another additive Gaussian absorption component was used to fit the feature at 0.57 keV. We used this model to estimate the equivalent width of the detected absorption feature at 0.57 keV. As the continuum level the absorbed blackbody model including the broad Gaussian line in absorption was used. With different levels (normalizations) of continuum and absorption lines an error of the equivalent width was determined. Results of the fit and equivalent width estimates are presented in Fig. 1.

<sup>1</sup> The RGS2 spectrum was used only for consistency checks; in the energy range of 0.5–0.59 keV it has a significantly reduced effective area owing to the failure of CCD4 in September 2000, see *XMM-Newton* Users Handbook



**Fig. 2.** Equivalent width of the absorption feature at 0.57 keV and blackbody temperature derived from the RGS spectra of RX J0720.4–3125 from three different epochs.

As already mentioned, RX J0720.4–3125 showed spectral variations, first noticed from the comparison of RGS spectra observed at different epochs (de Vries et al. 2004). After the detection of the absorption feature at 0.57 keV in the co-added RGS spectrum of RX J0720.4–3125, we examined its behavior over time. We divided all publicly available observations into three groups from different epochs. In the first group, we combined the RGS spectra of RX J0720.4–3125 from the year 2000 (ObsIds 0124100101 and 0132520301), for the second group the spectra between Nov. 2002 and May 2003 (0156960201, 0156960401 and 0158360201), and in the third group, the spectra from Oct. 2003 to Nov. 2007. This deviation was inferred from our recent study on the nature of global variations observed from RX J0720.4–3125 (Hohle et al. 2009) which was mainly based on the analysis of the EPIC pn data. In this way the variations in the blackbody temperature and the depth of the broad absorption feature in the spectra within each group of observations (see, Fig. 7, Hohle et al. 2009) are kept to a minimum and below the sensitivity of the RGS instrument. The results of this analysis are presented in Fig. 2. It shows a tendency for a reciprocal dependence of the measured equivalent width on the derived blackbody temperature. To decide whether this is due to pure flux (blackbody temperature) variations or to changes in the number of atoms in the line of sight, we fitted the three data sets with linked parameters of absorption features and the blackbody temperature was left free. The estimated equivalent widths are consistent with the variations when parameters of the narrow absorption feature were left free (Fig. 2). However, this needs confirmation with higher S/N ratio data sets.

### 3. Discussion

We report the detection of an absorption line at 0.57 keV in the *XMM-Newton* RGS spectra of RX J0720.4–3125. Since there is no uncalibrated instrumental feature in the energy range of 0.55–0.59 keV (21–22.5 Å), this line is clearly of astronomical origin. Whether it originates at the surface (atmosphere) of the neutron star, in its vicinity or in the interstellar medium is not clear a priori.

According to the atomic database ATOMDB<sup>2</sup>, a few relatively strong spectral lines are expected in the energy range of 0.56–1.0 keV (with a typical value of gravitational redshift of INS

<sup>2</sup> <http://xcx.harvard.edu/atomdb>

$\sim 0.2$ ) from plasma with a temperature of  $\sim 10^6$  K, mainly belonging to highly ionized oxygen (O VII, O VIII) and neon (Ne IX). Among them the O VII resonance  $K_\alpha$  spectral line at 0.574 keV has a maximal intensity and is compatible with our detection without any significant redshift. It is likely that the absorption feature consists of a number of blended absorption lines. However, given the data quality (i.e., spectral resolution and S/N ratio) it is difficult to identify all of them.

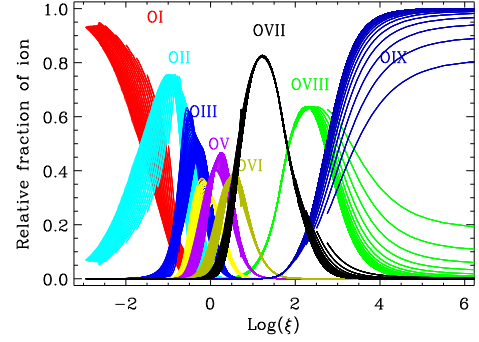
Moreover, similar absorption features were detected in high-resolution X-ray spectra of other galactic and extragalactic sources (*but not in all cases*<sup>3</sup> see, eg., Futamoto et al. (2004), Nicastro et al. (2005), Yao & Wang (2005), Fang et al. (2006), Bregman & Lloyd-Davies (2007)). This, as well as its relatively narrow nature (Chang et al. 2006; Paerels 1997), make it more plausible that it originates in the circumstellar/interstellar medium along the line of sight towards RX J0720.4–3125. Indeed, the estimates of strength of the magnetic field of  $B_{dp} \sim 2.4 \times 10^{13}$  G (from dipole braking) and  $B_{cyc} \sim 5.6 \times 10^{13}$  G (proton-cyclotron absorption feature) of RX J0720.4–3125 predict 20–60 eV broadening of spectral features originating in the magnetized atmosphere of the INS (Paerels 1997). Nevertheless, with a gravitational redshift of INS of  $\sim 0.16$ , a strong lines of O VIII at 0.653 keV are expected at 0.56 keV. In this case the O VII resonance  $K_\alpha$  spectral line from the INS atmosphere is expected at 0.49 keV. A very faint absorption feature is present in the spectrum of RX J0720.4–3125 (Fig. 1). However, given the fitted blackbody temperature ( $\sim 1$  MK) and the magnetic field strength (significantly increasing the binding energy of atoms) of RX J0720.4–3125, it is quite difficult to reconcile the presence of significant number of O VIII or other ions (e.g., Ne IX, with higher excitation temperature) in the atmosphere of RX J0720.4–3125.

If the detected absorption line has an origin in the circumstellar/interstellar medium, it may be identified with the highly ionized oxygen O VII. Indeed, according to the atomic database (ATOMDB) the strongest laboratory-measured spectral lines from O VII in the energy range 0.55–0.59 keV are: 0.5611, 0.5686 and 0.5740 keV. However, the first two spectral lines are forbidden and only in specific conditions (density  $\sim 10^{10} \text{ cm}^{-3}$ , as well as temperature  $\sim 1.5$  MK of “hybrid plasma”, i.e. photo-ionized and collisionally excited) may have a comparable intensity to the  $K_\alpha$  resonance line (Porquet & Dubau 2000, see their Fig. 11). Therefore, these two lines also may be excluded from further consideration, unless there is evidence of the presence of nearby, very high-density plasma of RX J0720.4–3125.

From the measured value of the equivalent width  $W_E = 1.35 \pm 0.3$  eV of the spectral line of O VII we estimate the number of ions (column density,  $N_{\text{OVII}}$ ) in the direction of RX J0720.4–3125 in two different ways. First, using the dependence of the equivalent width of the absorption feature on the column density of O VII (Futamoto et al. 2004), we estimated a lower limit of  $\log N_{\text{OVII}} = 15.8 - 16.2 \text{ cm}^{-2}$  in the direction of RX J0720.4–3125.

Second, we arrive at similar results,  $\log N_{\text{OVII}} \sim 15.9 - 16.1 \text{ cm}^{-2}$ , using the general relationship between measured equivalent width and number of atoms in the line of sight,  $W_\lambda/\lambda = 8.85 \times 10^{-13} N_j \lambda f_{jk}$ , where  $f_{jk} = 0.695$  is the oscillator strength of the O VII  $K_\alpha$  line (ATOMDB) and  $N_j$  is the column density (Spitzer 1978).

<sup>3</sup> Futamoto et al. (2004) did not detect the absorption line of O VII in the spectrum of Cyg X-2. According to Yao & Wang (2005), 3 of 10 Galactic low-mass X-ray binaries show absorption of O VII and/or O VIII.



**Fig. 3.** Ionization parameter  $\xi = L_X/(n_H r^2)$  of oxygen for different  $n_H = 10^1 - 10^9 \text{ cm}^{-3}$  volume densities located at the distance of  $r = 10^{10} \text{ cm}$  from ionizing luminosity  $L_X \sim 10^{33} \text{ erg s}^{-1}$  of a thermally emitting ( $T \sim 10^6 \text{ K}$ ) INS.

On the other hand, from the the average<sup>4</sup>  $n_{\text{OVII}} = (1.35 - 2.84) \times 10^{-6} \text{ cm}^{-3}$  and the distance to RX J0720.4–3125 ( $d = 360^{+170}_{-90} \text{ pc}$ , Kaplan et al. 2007) one obtains a value of 15.0–15.7  $\text{cm}^{-2}$  for  $\log N_{\text{OVII}}$ . Moreover, using a very recent estimate of the spatial density of the hot gas on the Galactic plane ( $n_H = (0.3 - 3.4) \times 10^{-3} \text{ cm}^{-3}$ , Yao et al. (2009)) based on Suzaku observations, we have the value of 14.0–15.3  $\text{cm}^{-2}$  for  $\log N_{\text{oxygen}}$  in the direction of RX J0720.4–3125.

This difference may be due to the origin of the absorption lines in the immediate, ambient environment of the INS. If the absorption feature at 0.57 keV originates in the ionized plasma near the INS and belongs to highly ionized O VII, then the presence of the absorption line itself may constrain the possible location (separation from RX J0720.4–3125) of the ionized cloud. Indeed, according to Tarter et al. (1969), if the plasma is located at a distance of  $r$  from RX J0720.4–3125, the ionization parameter  $\xi = L_X/(n_H r^2) = L_X/(N_H r)$  is strongly determined by the luminosity of  $\sim 10^{33} \text{ erg s}^{-1}$ . If so, oxygen will be fully photo-ionized at a distance  $r < 10^8 \text{ cm}$  (Kallman & McCray 1982, see, also Fig. 3).

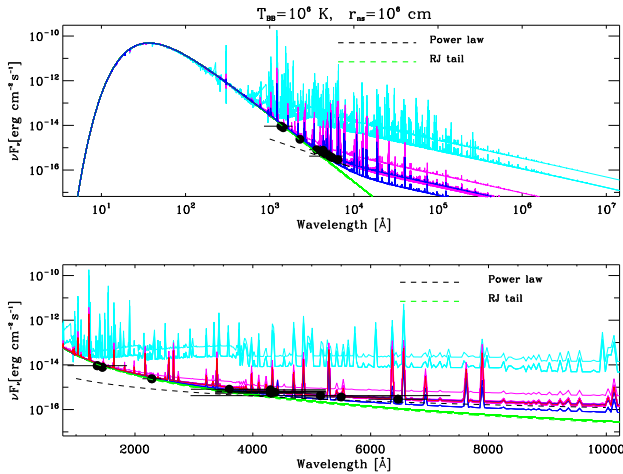
Moreover, in order to have a sufficient amount of O VII ions near a thermally emitting ionizing source with temperature  $\sim 10^6 \text{ K}$  and X-ray luminosity of  $L_X \sim 10^{32} - 10^{33} \text{ erg s}^{-1}$ , for the ionization parameter the condition  $1 < \xi < 10^3$  should be satisfied (Fig. 3). This means that a cloud/slab with rather high density (eg.  $n_H = 10^1 - 10^9 \text{ cm}^{-3}$ ) must be located within a distance of  $10^{10} < r < 10^{16} \text{ cm}$  from the ionizing source.

On the other hand, the hydrogen column density must be  $< 2 \times 10^{20} \text{ cm}^{-2}$  (from the EPIC pn spectroscopy), i.e. assuming oxygen abundance relative to the hydrogen  $n(\text{O})/n(\text{H}) = 4 \times 10^{-4}$  (Anders & Grevesse 1989), we obtain for oxygen a total column density  $N_{\text{oxygen}} < 8 \times 10^{16} \text{ cm}^{-2}$ .

Given the abovementioned general restrictions, a photo-ionized plasma associated with RX J0720.4–3125 may contribute to the observed fluxes in the UV and optical bands.

The optical and ultraviolet fluxes observed from rather faint, optical counterparts of thermally emitting INSs, in general, lie a factor of  $\sim 10$  above the extrapolated blackbody spectrum in X-rays (e.g. Kaplan 2008), the so-called “optical excess”. In the case of RX J1856.4–3754, the optical/UV

<sup>4</sup> Average  $n_H$  hot gas density estimated in the direction of 7 low-mass X-ray binaries (Yao & Wang (2005)), assuming oxygen abundance relative to hydrogen  $n(\text{O})/n(\text{H}) = 4 \times 10^{-4}$  (Anders & Grevesse 1989) and an ionic fraction of O VII  $\sim 1$  (see, Fig. 3).



**Fig. 4.** Simulated spectra of a photo-ionized plasma associated with a NS (blackbody spectrum  $T=10^6$  K and luminosity of  $10^{33}\text{erg s}^{-1}$ ) for different initial hydrogen volume densities, located at the distance of  $r_{\text{inner}} = 10^{10}\text{cm}$ . The filled dots indicate the observed optical/UV fluxes of RX J0720.4–3125 (Kulkarni & van Kerkwijk 1998; Kaplan et al. 2003; Motch et al. 2003; Eisenbeiss et al. 2009). For some parameter sets the simulated spectra can explain the power-law component with an “optical excess”.

spectrum is consistent with the slope of a Rayleigh-Jeans tail (van Kerkwijk & Kulkarni 2001; Burwitz et al. 2003), while for RX J0720.4–3125 there is a deviation and an additional power-law component was necessary to fit the data (Kaplan et al. 2003).

In order to estimate the contribution from a photo-ionized plasma near an INS, as mentioned above, we have used the widespread photoionization code CLOUDY (calculations were performed with version 07.02.02 of Cloudy, as described by Ferland et al. 1998). Despite the restrictions (luminosity of the ionizing source, ionization parameter, i.e. a combination of location of the cloud relative to the source and spatial density of the medium) there are still a number of free parameters for input to the CLOUDY code: Covering factor<sup>5</sup> (open or closed geometry), chemical abundances, filling factor, turbulence, etc.

Nevertheless, as shown by our simulations, in principle, the existence of a small, relatively dense ambient medium (e.g.  $n_{\text{H}} = 3.5 \times 10^8\text{cm}^{-3}$ , covering factor = 0.013, located at the distance of  $10^{10}\text{cm}$  from INS, see Fig 4), may at least partially explain the enigmatic “optical excess” observed at RX J0720.4–3125 (Motch et al. 2003; Kaplan et al. 2003) and provide sufficient O VII ions.

The satisfactory fit to the observed “optical excess” was not unique and may also be provided with other sets of parameters.

A partial origin of the absorption feature in the local, interstellar hot medium (e.g. Local Bubble) cannot be excluded completely. However, the *non-detection* of the absorption feature in other cases<sup>6</sup> beyond the Local Bubble (for other objects, see, Yao & Wang (2005), Fang et al. (2006), Bregman & Lloyd-Davies (2007)) makes the proposition of the

origin of the absorption feature mainly in the ambient medium of RX J0720-3125 more likely.

#### 4. Conclusions

1. An absorption feature at 0.57 keV is clearly detected in the co-added *XMM-Newton* RGS spectrum of RX J0720.4–3125. The detected absorption feature likely is a blend.
2. Most probably, it originates mainly in the ambient medium of RX J0720.4–3125 and may be identified with highly ionized oxygen (O VII), consisting of Doppler shifted components. Neither an interstellar nor an atmospheric, partial origin can be excluded completely.
3. The observed optical/UV flux excess of RX J0720.4–3125 compared to the extrapolated X-ray blackbody radiation partially may be caused by emergent emission of a nearby, relatively dense photo-ionized cloud. Further investigation, in particular simultaneous X-ray and optical short-term variations could shed some light on the nature of this enigmatic object.

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<sup>5</sup> The covering factor is the fraction of  $4\pi\text{sr}$  covered by gas, as viewed from an ionizing source, i.e.  $\Omega/4\pi$ . For details, see Ferland et al. (1998), CLOUDY documents

<sup>6</sup> The absorption feature is absent in the co-added RGS spectrum of RX J1856.4–3754 ( $d = 161^{+18}_{-14}\text{pc}$  (van Kerkwijk & Kaplan 2007)), but clearly seen in the co-added spectra of RBS1223 and RX J1605.3+3249 with lower significance (see, <http://xmm.esac.esa.int/BIIRD>)